The Impact of Sea Spray on Air-Sea Fluxes in Coupled Atmosphere-Ocean Models

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LONG-TERM GOALS

The goal is to investigate, theoretically and through analyzing existing data, the role that sea spray plays in transferring heat, moisture, and momentum across the air-sea interface, especially in high winds. Ultimately, I hope to develop simple parameterizations for these air-sea fluxes for use in large-scale models, especially those simulating tropical and extra-tropical storms.

OBJECTIVES

The ultimate goal of this work is to understand the physics and, thus, how to parameterize the air-sea fluxes of momentum and sensible and latent heat at all wind speeds. Since the COARE bulk flux algorithm (Fairall et al., 1996) is successful at winds speeds of 10 m/s or less, I focus on higher wind speeds, where sea spray is present and is a likely transfer agent. Succinctly, the first objective is to learn how to partition the air-sea fluxes between interfacial and spray contributions. The sum of the net sensible and latent heat fluxes via all routes is called the total enthalpy flux. Because this total enthalpy flux, rather than the individual sensible and latent heat fluxes, provides the energy for tropical storms, the second objective is to develop a parameterization for the air-sea heat fluxes—including spray effects—that is suitable for use in large-scale, coupled air-sea interaction models. The third objective focuses on air-sea momentum exchange in high winds and on how spray and other surface disruptions alter this exchange.

APPROACH

This work is theoretical and analytical; there has been no experimental component. Microphysical theory establishes how rapidly spray droplets can exchange heat and moisture in a given environment. Theoretical considerations also predict how the sea spray generation function should depend on wind speed. The analytical part involves developing parameterizations for the various processes under consideration by simplifying model results or by synthesizing various data sets and observations reported in the literature. Checking the parameterizations being developed against available data is also another aspect of what I call analytical work.

Theory and microphysical modeling suggest we can estimate the total (i.e., both interfacial and spray) air-sea latent ($H_{L.T}$) and sensible ($H_{s,T}$) heat fluxes as (e.g., Andreas and DeCosmo, 1999)

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14. ABSTRACT

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$$H_{L,T} = H_L + \alpha Q_L , \tag{1}$$

$$H_{s,T} = H_s + \beta Q_S - (\alpha - \gamma) Q_L . \tag{2}$$

Here, H_L and H_s are the so-called interfacial fluxes that I estimate with the COARE bulk flux algorithm (Fairall et al., 1996), and Q_L and Q_S are nominal spray latent and sensible heat fluxes predicted by Andreas's (1992) microphysical model. α, β, and γ are small, nonnegative coefficients obtained by tuning (1) and (2) with data.

WORK COMPLETED

One of the main knowledge gaps in this field is the form of the sea spray generation function. This quantifies the rate at which sea spray droplets of initial radius r_0 are produced at the sea surface—as a function of wind speed, for example. This function is necessary for computing Q_S and Q_L above but is uncertain because it is so difficult to measure.

Several suggestions as to the form of the spray generation function are available in the literature. I have reviewed these to see if they suggest any consensus (Andreas, 2001). Figure 1 shows what the literature gives for the volume flux of spray droplets of radius r_0 for a 10-m wind speed (U_{10}) of 20 m/s. At any given radius, the figure shows a six-order-of-magnitude range for this crucial function. This uncertainty highlights the problem here; but of course, not all of these functions can be correct.

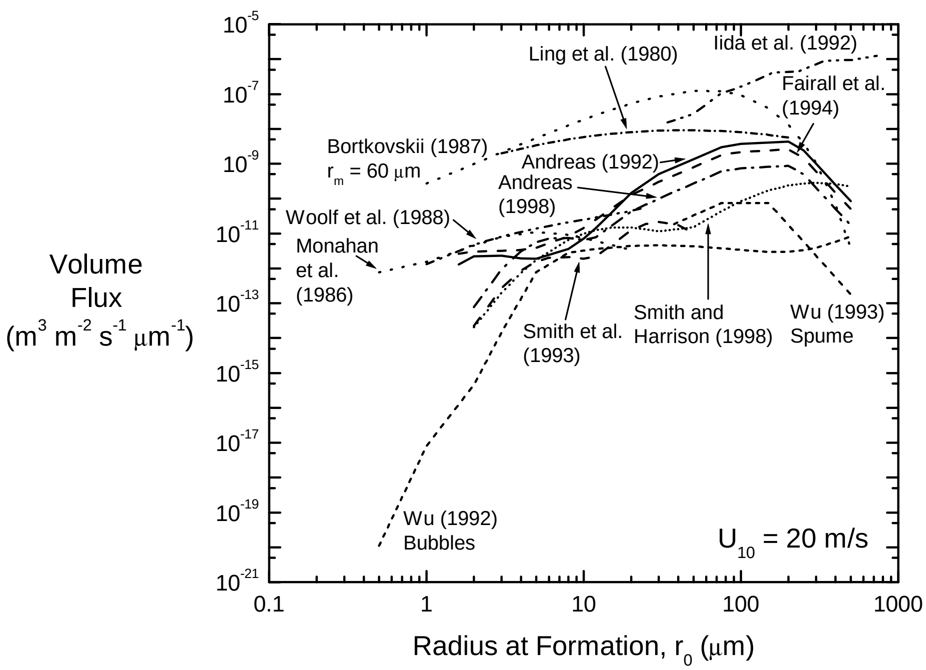

Figure 1. A sampling of sea spray generation functions from the literature for a 10-meter wind speed of 20 m/s. Here the spray generation function is depicted as a volume flux—the volume of spray droplets with initial radius r_0 produced per square meter of sea surface per second per micrometer increment in droplet radius.

After invoking some theoretical constraints and evaluating indirect evidence, I identified four of the functions in Figure 1 that have the proper theoretical dependence on wind speed and yield reliable magnitudes for the spray generation function for droplet radii between 1 and 500 μm. Those functions are the ones from Andreas (1992), Fairall et al. (1994), Andreas (1998), and Smith and Harrison (1998) [after modifications described in Andreas (2001)]. Each of these functions is useful for winds up to 20 m/s, while the Andreas (1998) and the modified Smith and Harrison (1998) functions are useful for speeds up to 30 m/s.

In collaboration with Kerry Emanuel at MIT, I have been trying to adapt my analyses based on (1) and (2) above into parameterizations that are useful for large-scale models of tropical and extra-tropical storms. We have finally developed physically and empirically based parameterizations for the spray enthalpy and momentum fluxes and have incorporated these successfully into Emanuel's (1986, 1995) axi-symmetric tropical cyclone model (Andreas and Emanuel, 2001).

RESULTS

My review of the available sea spray generation functions (Andreas, 2001) suggests that we may know more about spray generation than a casual viewer of Figure 1 might conclude. The four most reliable functions that I identified—the ones from Andreas (1992, 1998), Fairall et al. (1994), and Smith and Harrison (1998, though modified somewhat by me)—agree within half an order of magnitude, compared to the six-order-of-magnitude spread in Figure 1. The function from Fairall et al. (1994), in particular, seems especially useful because its form would let us easily extrapolate it beyond its stated upper wind speed range of 25 m/s into hurricane-strength winds.

The tropical cyclone simulations—with spray effects included—that I have been doing with Kerry Emanuel suggest that spray can be an important agent in setting the intensity of these storms. Emanuel (1999) has been successful in reproducing the intensity of historical hurricanes with his simple thermodynamic model although that model parameterizes the surface fluxes of enthalpy and momentum simply with equal transfer coefficients that depend linearly on wind speed. In contrast, theory suggests that the enthalpy transfer coefficient should decrease with increasing wind speed. Though measurements in high winds definitely show that the momentum transfer coefficient increases, they have been inconclusive as to the behavior of the enthalpy transfer coefficient. Because Emanuel's (1986, 1995) model is thermodynamically accurate and has yielded successful predictions of storm intensity, we assume that there must be some truth in the near-equality of the enthalpy and momentum transfer coefficients in high winds. We therefore speculate that spray-mediated exchange can explain this enhanced enthalpy transfer in Emanuel's model.

Figure 2 shows our simulations of storm intensity (quantified as the maximum azimuthal surface-level wind speed) using Emanuel's model and this spray hypothesis. The "Control" run is Emanuel's standard model. In the "Wave Drag Only" simulation, we modeled the increase in momentum flux with wind speed using the Charnock relation. This run demonstrates that a realistic wave parameterization without compensating enthalpy transfer produces a storm of only modest intensity.

In the "Spray Enthalpy and Momentum" run, we based spray parameterizations on our HEXOS analysis (Andreas and DeCosmo, 1999, 2001) and theoretical considerations. Here the spray enthalpy flux causes the storm to intensify, while the spray momentum flux retards it. Finally, when we

combined both spray and wave drag effects (i.e., “All Effects”), the model produces a storm with intensity similar to the control run’s. We conclude that realistic parameterizations for spray enthalpy and momentum transfer can explain the success of simpler tropical cyclone models that invoke seemingly unrealistic air-sea transfer parameterizations.

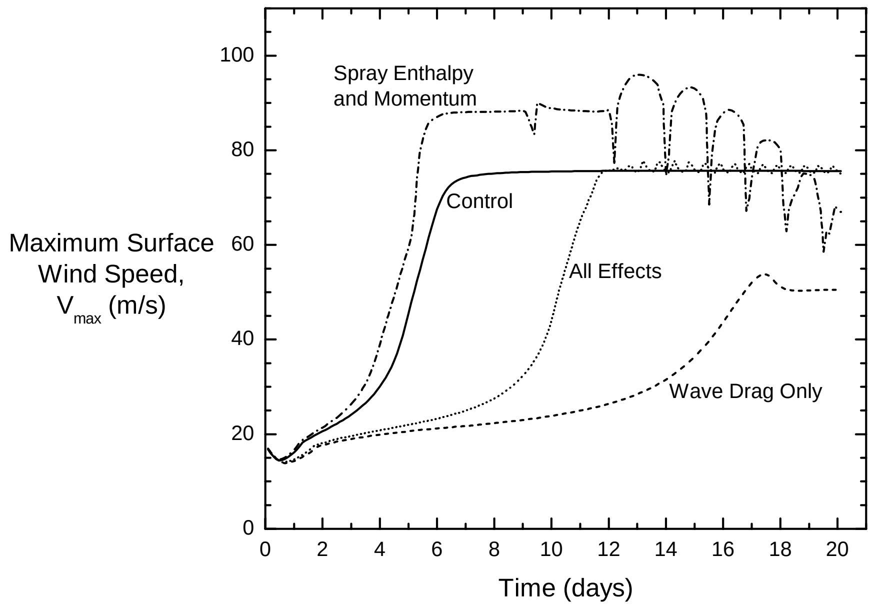

Figure 2. Evolution with time of the maximum surface wind speed, V_{max} (a measure of the storm’s intensity), in four integrations of Emanuel’s (1995) tropical cyclone model. The “Control” run uses identical exchange coefficients for enthalpy and momentum. The “Wave Drag Only” run simulates wave effects on the drag coefficient using the Charnock relation and a comparable parameterization for the enthalpy transfer. The “Spray Enthalpy and Momentum” run includes a parameterization for spray enthalpy and momentum fluxes but includes no wave drag. The run with “All Effects” includes both spray and wave parameterizations.

IMPACT/APPLICATIONS

The role of sea spray in mediating the air-sea fluxes in high winds is a central theme in ONR’s new CBLAST initiative (for Coupled Boundary Layers and Air-Sea Transfer). Perhaps parochially, I believe this focus is in part due to my research on sea spray over the last decade. I have identified the spray generation function as a crucial unknown and, in particular, have shown that we must understand the production of spume, the largest spray droplets, to improve the spray generation function. My modeling has also shown the potential magnitude of spray effects on the surface fluxes and has suggested the wind speed dependence of these effects.

My reanalysis of the HEXOS data set with Janice DeCosmo finally identified what the signature of spray-mediated heat fluxes looks like for winds up to almost 20 m/s. That is, in winds nominally above 12 m/s, the usual bulk flux algorithms, such as the COARE algorithm (Fairall et al., 1996), tend

to underpredict both the surface sensible and latent heat fluxes because they do not account for spray's ability to transfer heat and moisture.

On the basis of this HEXOS analysis, Kerry Emanuel and I have developed parameterizations for the spray-mediated enthalpy and momentum fluxes and tested these in Emanuel's simple tropical cyclone model. These parameterizations can be the basis for spray parameterizations in other large-scale, coupled models being developed under CBLAST.

TRANSITIONS

Besides the papers I have written to describe my spray research, other, more direct transitions of this research are through my collaborations with Kerry Emanuel at MIT, Wade McGillis at WHOI, and Will Perrie at Bedford Institute. These collaborations involve developing parameterizations for air-sea transfer in high winds that acknowledge the role played by sea spray and other surface disruptions.

RELATED PROJECTS

The Division of Atmospheric Sciences at the National Science Foundation is currently funding me for a three-year project to study "Air-Sea Fluxes at High Wind Speeds with Application to Tropical Cyclone Intensity Prediction." I am collaborating in this work with Wade McGillis and Jim Edson of WHOI, Tetsu Hara and Isaac Ginis of the University of Rhode Island, and Kerry Emanuel of MIT. I also have leveraged my ONR funding by collaborating on spray research with scientists outside CRREL who are funded by projects at their own institutions. For example, the publications listed below document collaborations with Janice DeCosmo at the University of Washington and Stephen Belcher at the University of Reading.

I am a member of the PhD. thesis advisory committee for Magdalena Anguelova in the College of Marine Studies at the University of Delaware. She is working on a thesis topic complementary to my own research, "Sea-Salt Aerosols: Their Generation and Role in Climate Systems."

Finally, I have convinced Darren Hitt, a mechanical engineering professor at the University of Vermont, and his master's student that spray is an important and interesting topic. They are currently preparing a laboratory experiment, with me as an advisor, to investigate how spray can transfer heat across an air-water interface.

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